

Comprehensive Shuttle Foam Debris Reduction Strategies

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Nomenclature

Al	= Aluminum
ALARA	= As Low As Reasonably Achievable
C	= Carbon
CAIB	= Columbia Accident Investigation Board
CEV	= Crew Exploration Vehicle
CFC	= Chlorofluorocarbon
CLV	= Crew Launch Vehicle
ET	= External Tank
FAST	= Functional Analysis Systems Technique
FTIR	= Fourier Transform Infrared Spectroscopy
FT-NMR	= Fourier Transform ¹³ C Nuclear Magnetic Resonance
H	= Hydrogen
HCFC	= Hydrochlorofluorocarbon
HPLC	= High Performance Liquid Chromatography
IFA	= In-Flight Anomaly
IPT	= Integrated Product Team
LEO	= Low Earth Orbit
LH2	= Liquid Hydrogen
LOX	= Liquid Oxygen
MAF	= Michoud Assembly Facility
MDI	= Diphenylmethane Diisocyanate
MMOD	= Micrometeoroid and Orbital Debris
MSFC	= Marshall Space Flight Center
N	= Nitrogen
NDE	= Non-Destructive Evaluation
O	= Oxygen
PAL	= Protuberance Aero Load
RTF	= Return to Flight
TGA	= Thermogravimetric Analysis
TRL	= Technology Readiness Level
WLE	= Wing Leading Edge
VSE	= Vision for Space Exploration

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I. Introduction

The Columbia Accident Investigation Board (CAIB) was clear in its assessment of the loss of the Space Shuttle Columbia on February 3, 2003. Foam liberated from the External Tank (ET) impacting the brittle wing leading edge (WLE) of the orbiter causing the vehicle to disintegrate upon re-entry. Naturally, the CAIB pointed out numerous issues affecting this exact outcome in hopes of correcting systems of systems failures any one of which might have altered the outcome. However, Discovery's recent return to flight (RTF) illustrates the primacy of "erosion" of foam and the risk of future undesirable outcomes. It is obvious that the original RTF focused approach to this problem was not equal to a comprehensive foam debris reduction activity consistent with the high national value of the Space Shuttle assets.

The root cause is really very simple when looking at the spray-on foam insulation for the entire ET as part of the structure (e.g., actual stresses > materials allowable) rather than as some sort of size/time limited "ablator." This step is paramount to accepting the CAIB recommendation of eliminating debris or in meeting any level of requirements due to the fundamental processes ensuring structural materials maintain their integrity. Significant effort has been expended to identify "root cause" of the foam debris In-Flight Anomaly (IFA) of STS-114. Absent verifiable location specific data pre-launch (T-0) and in-flight, only a most "probable cause" can be identified. Indeed, the literature researched corroborates NASA/TM-2004-213238 disturbing description of ill defined materials characterization, variable supplier constituents and foam processing irregularities.¹ Also, foam is sensitive to age and the exposed environment making baseline comparisons difficult without event driven data. Conventional engineering processes account for such naturally occurring variability by always maintaining positive margins. Success in a negative margin range is not consistently achieved.

Looking at the ET's spray-on foam insulation as part of the structural system (e.g., "glass half full" mentality) will create an environment where ET debris levels as low as reasonably achievable (ALARA) can be realized. ALARA is a NASA requirements philosophy deployed for the complex, mission altering radiation exposure requirements for life safety of astronauts. In the Shuttle's case, reasonableness is established by exhaustive engineering rigor, allowable debris size/quantity, technology maturity and programmatic constraints.

A more robust urethane foam thermal protection system (TPS) will enhance the functionality of the new Ares I Crew Launch Vehicle (CLV) Upper Stage. This paper will outline the strategy for a comprehensive effort to reduce ET foam debris and outline steps leading to an improved foam TPS. The NASA must remain committed to such an approach no matter what becomes of the next flight's actual debris field lest we fall back into a false sense of security. This commitment along with full implementation of all the other CAIB recommendations such as orbiter hardening will significantly improve the Shuttle system, the engineering workforce, future capabilities & alternate policy off-ramps, national human resource protection, high value national asset protection and increase the level of service to the overall NASA mission.

II. Materials & Mechanistic Behavior

The Space Shuttle External Tank (ET) is covered with multiple urethane foams both sprayable and pourable. They belong to basically two categories of urethane foams, polyurethane and polyurethane isocyanurate (PUIR) foams. The foam “systems” are comprised of parts A & B from raw materials originating from multiple sources. Part A is the isocyanate and Part B is the polyol, catalysts, surfactants and the blowing agent. The Parts A & B are then proportionately sprayed or “poured” at a specified ration onto the aluminum substrate of the ET and in an exothermic reaction form a protective closed cell foam insulation structure. The polyurethane foams such as PDL-1034, a polyether and BX-265, polyester, are utilized primarily in manually applied regions of the tank such as protuberance regions, ramps, collars and other complex geometric closeout locations. The PUIR foams such as NCFI (North Carolina Foam Industries) 24-57 and 24-124 utilize an excess of isocyanate or higher isocyanate index (Part A/B ratio) to create foams having better thermal stability than the polyurethane foams. The NCFI 24-57 and 24-124 are utilized on the acreage regions of the tank primarily applied by automated spraying techniques with controlled conditions.

Polyurethanes contain carbamate groups, -NHCOO- , also referred to as urethane groups, in their backbone structure.² In general, urethane foams encompass both polyurethane and PUIR foams formed in the reaction of an isocyanate with a macroglycol, a so-called polyol based on polyethers, polyesters, or a combination of both. The stiffness associated with these foamed polymers is a product of the chemistry of the materials. In the realm of the solid state physicist and quantum chemist, the stiffness of these highly cross linked covalent bonded polymers can be estimated based on their chemical structure. Higher strength foams can be realized through higher functional polymeric isocyanates and higher functional polyols. These increase the covalent cross link density and results in an increase in the Young’s modulus for the resultant foam. Additionally, cross linking is achieved through secondary reactions such as the trimerization of part of the isocyanate groups during formation of PUIR foams. However, there are many trade-offs with regards to the final chosen chemistry. Catalysts are added to overcome acid impurities, enhance secondary linkage and control/balance the reactivity of the system. Surfactants are added to facilitate the formation of small bubbles necessary for a fine cell structure. Blowing agents have presented great challenges for NASA and the industry having to pursue non-CFC-11 versions. Alternative blowing agents such as HCFC’s and HFC’s have λ -values ($\text{m}^2\text{W}/\text{m}^2\text{K}$) of about 19.5 whereas CFC-11 blown foams have a value of 18.0 making the alternatives less efficient in their insulation performance due to the fact that the blowing agent accounts for 97% by volume of gas in these low density materials.² For instance, the PDL-1034 formulation utilizes a HCFC-141b and a little water which generates carbon dioxide as part of the blowing agent. Water affects the flow properties during the reaction period wherein the chemicals move from the low viscosity state of the original liquid mixtures to the polymerized foam. The configuration of the substrate can hinder the effective flow from initial “creaming” to the end of the rise during the foam expansion process and determines whether areas will be automatically sprayed, manually sprayed or poured. Similar to good chemistry, good flow is necessary to produce as close to an isotropic TPS material as possible.

Closed cell urethane foams are a large family of flexible and rigid products the result of a reactive two part process wherein a urethane based polyol is combined with a foaming or “blowing” agent to create a cellular solid at room temperature. The ratio of reactive components, the constituency of the base materials, temperature, humidity, molding, pouring, spraying and many other processing techniques vary greatly. However, these conditions have a great impact on the final material properties. The cell wall thickness of typical rigid polyurethane foam is from $3\mu\text{m}$ at cell faces to $30\mu\text{m}$ at cell edges.¹ From one of the author’s recent test samples, Figure 1 is a photomicrograph view of typical polyurethane foam at the cell level.

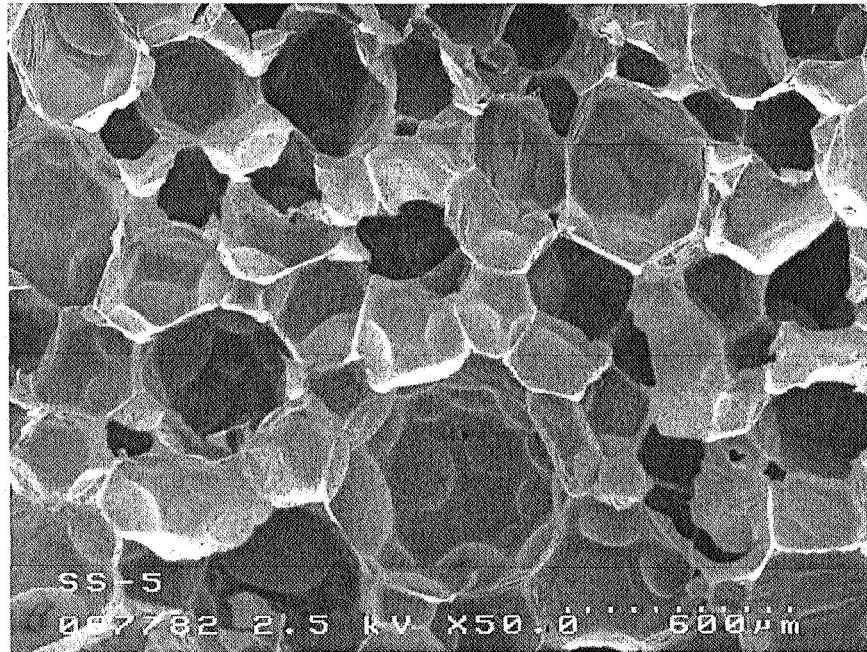


Figure 1 – Polyurethane Foam Cell Structure

Typically, the constituencies of closed cells in urethane foams is more than 90% throughout the foam material, but note the presence of voids in Figure 1. Ideally, a foam cell structure exhibiting uniform spherical cell shapes, negligible voids and consistent cell wall thickness would provide a reliable engineering material. However, PUIR and polyurethane foams in practice exhibit reaction directional cell elongation, void agglomeration and variable cell wall thickness. These characteristics produce a foam structure of higher material mechanical properties in the foaming reaction rise direction than the transverse direction, higher gas pressures during ascent in “large” void locations and wide variances in material mechanical properties. On the ET, the thickness is approximately 1” throughout the acreage with thicker foam in and around protuberances, ramps and transitions.

The study of the erosion of polyurethane foam under dynamic aerospace environments dates back to the Saturn program when engineers were working on a replacement for the cumbersome external insulation system for the S-II stage. Even though the in-line configuration posed little risk for loss of life, there was rigorous discipline assuring

“insulation must remain structurally intact”⁷ to meet functional requirements of heat leak and boil-off. This stepwise approach in clearly establishing requirements and executing a comprehensive insulation development program led to the foam technologies successfully inserted on Saturn and parent of today’s foam systems.

The mechanistic findings of these earlier studies are still applicable today:

- 1) Foam not processed properly, especially with respect to mixture ratio (NCO/OH), showed evidence of spalling with rapid deterioration.⁷
- 2) Materials properties evaluations (e.g., physical, chemical & mechanical properties) are needed at the component level prior to mixing, just after mixing and the cured foam at beginning/end of design life.
- 3) Heat sink effects drawing heat away from the foaming process at a rate sufficient to prevent boiling of the blowing agent can lead to a high density foam layer at the foam surface interface.⁷
- 4) Low density polyurethane foams degrade rapidly when exposed to the external environment attributable primarily to ultraviolet (UV) exposure. Moisture alone does not result in any significant foam degradation effects.⁷
- 5) Wind tunnel testing at room temperatures reveal no damage to foam panels at dynamic pressures 40% greater than Saturn S-II stage maximum design values (e.g., @ multiple protuberances) and no loss in intentionally de-bonded foam plugs with coatings applied.⁷
- 6) Thermal vacuum tests reveal BX-250 foam cell walls beginning to burst at ~250°F.⁵
- 7) X-15 flight tests closely approximating predicted Saturn S-II combined environment design values show foam erosion in protuberance influenced regions of approximately double that of lower temperature areas.⁵

These extensive studies and testing provided great insight into how the foam fails and other forensic observations. Certainly, these forensic observations and studies do not address the geographical dispersion of ET failures within a time dependent framework, but serve as a benchmark for understanding failure modes. The initiating effect during ascent triggering foam failure is the increase in temperature during aerodynamic heating. This increase in temperature decreases the strength of the foam cell walls while increasing the internal gas pressure until rupture of the cell wall occurs. These particles enter the boundary layer possibly creating downstream damage. In any case, the erosion accelerates exposing more irregular surfaces to aerodynamic viscous forces with an unpredictable path of degradation. It is conjectured that the loss in cell wall strength due to increased temperatures is irreversible and foam erosion continues well beyond maximum aerodynamic shear possibly more a function of thermal dissipation at that point.⁵

III. Integrated Process

The importance of detailed foam chemical information has been reported by NASA from the time of its initial use. In August 1988, Harvey, et.al., report, “A major defect in all of the systems (foam) according to NASA is the lack of detailed chemical information.”²

This theme has been repeated throughout the literature researched, as well as, supplier

problems, quality control and inspection. Establishing realistic requirements for ET foam loss that can be verified and validated necessitates stringent process controls, materials quality verification, acceptance testing and rigorous certifications. Today, these problems may have been overcome and are reduced to an examination of when such evaluations are conducted, the sample frequency and the event driven nature of their conduct.

The comprehensive foam reduction strategy presented in this paper is a multi-tiered approach aimed at short and long term solutions with ET debris limitation requirements driven by the physical mechanics of materials properties. "Fly as is" decisions aside, strict adherence to the precedence of the systems engineering requirements allocation, functional analysis and verification processes will guide the conduct of ET program execution. Separately, waivers and deviations from these known engineering standards can be processed at the element integration level. ET must verify by positive, combined environmental testing or flight experience that minimum foam debris loss standards can be met. Absent this positive proof, other risk reduction techniques, assessments by analysis (justification must be made for depending solely on Monte Carlo analysis and data generated from low resolution photographs), contingency plans and programmatic mission needs may provide sufficient flight rationale. However, the true state of the ET subsystem must be clearly presented to decision makers at Flight Readiness Reviews (FRR), Certificate of Flight Readiness (CoFR) and ultimate Independent Technical Authority (ITA) decision level. Estimation techniques applied to poor quality photographs to derive data can lead to error propagation in large programs such as Shuttle. Data integrity is paramount in preventing misuse and the resultant poor decisions. Review of Powerpoint charts presented to the ITA decision making authority for STS 114 (Discovery) highlights the dangers of such error propagation. The true debris generation state of the ET and its verified compliance with requirements was not fully disclosed. More importantly, requirement waivers were not known to have been generated. STS-121 by contrast was a major improvement, but data integrity issues still evident.

Short term solutions include a series of further debris reduction activities as follows:

- 1) Exhaustive NDE, testing and reapplication of foam in protuberance influenced regions for delivered tanks. Execute waivers on any tanks determined suitable for flight rationale for any foams and/or tank regions not validated by statistically significant combined environments testing and comprehensive NDE results.
- 2) Redesign Ice Frost Ramps (IFR's) (including elimination/reduction of TPS), protuberance influenced insulation material, NDE and testing of delivered tanks. Execute waivers on any tanks determined suitable for flight rationale for any foams and/or tank regions not validated by statistically significant combined environments testing and comprehensive NDE results.
- 3) Remove and replace all low probability PONEA (Probability of Not Exceeding Allowable) location foam on delivered tanks. Execute waivers on any tanks determined suitable for flight rationale for any foams and/or tank

regions not validated by statistically significant combined environments testing and comprehensive NDE results.

- 4) Use “As is.” Limit risk to loss of life by flying with significantly reduced crew and full consideration of contingency operations. Execute waivers on any tanks determined suitable for flight rationale for any foams and/or tank regions not validated by statistically significant combined environments testing and comprehensive NDE results.

Based on literature and past experience, long term solutions should include the full gamut of development activities to ensure structural integrity of foam in meeting debris loss limitations as follows:

- 1) Coatings – Paint, membranes and other high heat resistant barriers that can maintain the aerodynamic surface during the first few minutes of flight.
- 2) Fiber Reinforcements – This will include building on the current body of knowledge on polyurethane foams to optimize a formulation with high heat resistance and higher strength. Fiber reinforced foams offer a very high promise of being able to increase strength and further research/development is necessary.⁴
- 3) Combination Systems – Each of the new foam formulations and coatings need not only be examined separately in meeting requirements, but in combination with one another.

IV. Requirements

The primary requirements limiting debris generation are documented in NSTS and other internal NASA documents. These prescriptions include great detail on location and allowable debris size. The author prefers a conservative zero defects approach in defining a program that will be based on the highest probability of success. High expectations are not unreasonable given the nature of this problem. This necessarily creates “derived” requirements of “no debris generation” in a comprehensive external tank foam debris reduction project.

The root causation “erosion” due to aerodynamic heating and viscous forces is fundamental in defect free and defective foam alike. Naturally, defective foam areas have higher probability of release. There are basically four primary defects; 1) Bondline Delamination, 2) Low Material Properties (e.g., Bond Adhesion, Cohesive failure), 3) Threshold Voids and 4) Cracking. All four defects can be eliminated from a mission through comprehensive NDE, materials quality control and/or materials improvement initiatives. Inability to manufacture a TPS free of these defects introduces an unnecessary delta pressure and cryopumping mechanism possibly contributing to the primary aeroheating/loads causation for potential foam loss depending on size and location.

The large volume between the LO2 tank and the LH2 tank is covered by the “intertank flange”, a structural section of the tank enclosing the interstitial volume between the top dome of the LH2 tank, and the bottom dome of the LO2 tank. Prior to launch, this volume is on a continual purge with nitrogen, to eliminate oxygen from the volume.

During tanking, the liquid hydrogen tank is at -423°F . At this temperature, nitrogen condensation can form on the top dome of the LH2 tank, and drain down to the LH2 tank/intertank flange interface. Because of the design, there are potential leak paths for this liquid to the exterior, or foam side of the structure. If voids are present at the foam structure interface, the liquid can fill the void. This phenomenon is known as “Cryo-ingestion”. On ascent, external aerodynamic heating can cause subsequent sublimation and hence foam release at that interface. Cryo-ingestion is a threat only at the LH2 intertank flange region of the ET. The larger acreage of the tank is not susceptible since the liquefied nitrogen condenses on the top dome of the LH2 tank and runs down to the intertank flange interface. Only voids in this immediate area are susceptible to cryo-ingestion. The ET tank foam is closed-cell foam, so liquids will not pass through the foam unless other leak paths are present, and cryo-ingestion can only occur if liquid can transfer into the void. Manufacturing and processing controls have been put in place to improve the intertank flange closeout, and minimize flaws and flaw sizes in the ET foam.

There is another potential source of cryogenic problem specific to the LH2 tank known as “cryo-pumping”. The extremely cold temperatures of the hydrogen tank also bring about this phenomenon. If a flaw in the foam is sufficiently close enough to the tank surface to reach -423°F , the atmosphere trapped in the foam void will liquefy. If there is also a “leak-path” from the atmosphere to this void, the liquefaction occurring inside the void causes the air pressure in the void to drop and draw in more air through the leak path. This process continues until the void is full of liquefied atmosphere. On ascent, heating causes the liquefied air to change state to gas, and pressurize the void. If this heating occurs at a rate sufficiently fast that the leak-path cannot vent the gas, foam loss can occur, with foam structural failure likely initiating along the leak path. Cryo-pumping represents a threat that exists across a large acreage of the top of the LH2 tank, but will only occur if voids reach critical temperatures, and have leak-paths to the atmosphere. Further, as the distance below the intertank flange increases, ascent heating decreases. Thus, at some point below the intertank flange, the threat from cryo-pumping ceases.

The timeframe of concern is very limited in the case of Shuttle due to loss of atmosphere with gain in altitude (debris) and the cryogenics contained in the ET are not needed on-orbit (thermal function). Aerodynamic Sensitive Transport Time (ASTT) is the period from liftoff (T-0) to approximately T+136 seconds when the vehicle is at about 180,000 ft. in altitude and traveling at about Mach 4.2 (See Figure 2) depending on many variables. At this altitude, the transport mechanisms creating a debris hazard have dissipated. The Ares CLV US TPS will need to perform functionally (e.g., maintain minimum thermal properties) on-orbit for periods of time possibly in excess of 90 days. At these higher altitudes, “pop-corning” of TPS is typically comprised of small pieces of foam liberated due to the less than threshold value voids reacting to a more extreme “vacuum” environment.

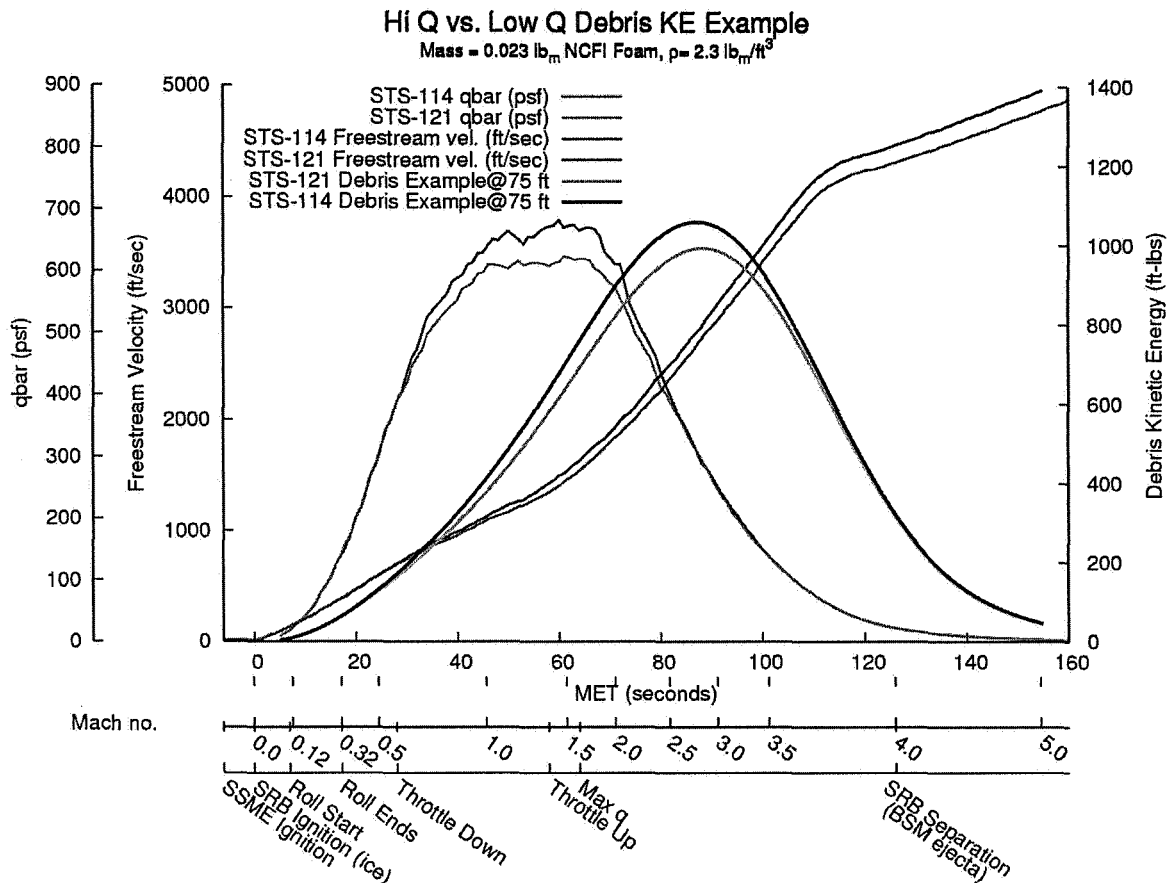


Figure 2

Root causation erosion can be intensified depending on flight profiles as recently shown on STS-121 analysis. Trajectory, aeroheating and LH2 Liquid Level indications are that a STS-121 High Q mission design may have caused earlier foam loss, additional foam loss and more damage if impacts occurred (See Figure 2).²⁸ Additionally, this same analysis correlates log transformed “estimated” mass losses to maximum dynamic pressure (MaxQ) for IFR acreage combined losses (void-delta P, cryopumping and aerodynamic not singled out based on photographic image data). The report describes the increasing mass to MaxQ trend line as significant. Although the report emphasizes the author’s concern with utilizing poor quality 2-D photographs to generate 3-D “data,” it is important to note that “there is no meaningful correlation” with such historically “generated” data and the three key factors of void-delta P, cryopumping and aerodynamic effects. It seems unlikely that aerodynamic effects would not correlate well with MaxQ and skepticism of the historically generated photograph data increases especially with regards to “root cause” designation. This author believes that such healthy skepticism has finally arrived within the Shuttle Program Office and future testing will bring “root cause,” as-designed, as-built and defective materials into their proper perspective. The important take-away or lesson learned from this complex failure mode analysis is that strength of materials and loads environment are paramount for root causation. When actual stress becomes greater than material allowable failure occurs. “Structures” such as

TPS designed without statistically relevant positive margins can and will fail. Where, when and how depends on which part of the equation becomes apparent first.

Absent location specific flight stress/strain/temperature data on the ET and “A-basis” materials data, the significance of any materials improvements needed will remain not quantified. As reported by Kraus⁵, flight sensor data must be carefully scrutinized when approaching physical margins. The multiple non-linear analyses required to operate vehicle structural systems at these razor thin margins is unproven and adds further credence to a positive margin “no debris” requirements philosophy. Stuckey in 1996 reported that at 0.0178 in/in strain to failure of tested NCFI 24-124 (current acreage foam) that this level was unimportant as “the ET does not see strains to this level⁸.” This suggests the magnitude of foam materials improvements is a fractional rather than multiple measure. Regardless, proceeding with a debris reduction project without such location specific quantification of worst case environments especially elevated temperature/strain is a mild risk. Other requirements risks especially for short term tasks include the absence of actual location specific data to substantiate early stage foam loss failure modes possibly resulting in incomplete NDE. However, the phased approach to the program and a conservative requirements philosophy will allow such parallel analyses and a wide range of performance enhancements to be implemented over time mirroring current national policy and agency strategy.

The argument that schedule and qualification requirements preclude new foam formulations is not based on fact. Several foam materials improvement projects and ET design changes have been initiated in the past resulting in successful flight integration within 2 years. The PAL ramp “redesign” was qualified in just six months for flight on STS-121. A comprehensive foam refinement project may result in a series of improvements over the next 4 years. An innovative industry wide competition may produce results in 12 months. At the beginning of the first RTF, the same programmatic logic was used and 2-1/2 years later we are still struggling for answers. The zero defects charter is the only practical approach to establishing a successful debris reduction project. It is precisely these margins that have never before existed for ET foam and it will be the quest of such margins that brings significant reduction in ET debris generation.

V. Materials Improvement Initiatives

This paper highlights longer term materials improvement initiatives for addressing root cause as previously discussed in the background material. This philosophy accepts the variability of the materials and processes as they are and establishes statistically significant positive margins to meet requirements. However, the current short term ET NDE developments and materials quality control efforts must incorporate relevant key findings/results of materials improvement initiatives. For example, recent research indicates that non-uniformity of cell shape in closed cell cellular solids decreases bulk Young’s modulus and shear modulus.⁶ New NDE techniques might need to be developed should it be determined that sensitivity to cell shape or size becomes an important means of assessing foam condition and flight readiness. The age/shelf life of completed tanks and raw materials is another critical characteristic that may be reassessed after key

findings/results and change constraints for flight. The materials improvement initiatives should be viewed as integral to a successful short term strategy and not in competition.

Materials improvement initiatives should fall under two broad and overlapping categories; 1) existing foam characterizations & improvements and 2) new foam system formulations.

Existing foam characterizations & improvements – The raw materials of ET's polyurethane/polyisocyanurate foam system depends heavily on the supplier, the materials lot or batch, storage/inventory/shipping history and real time mixing data. Detailed chemical analyses are necessary to establish a baseline and to affect mandatory inspection points (MIP) for quality control. The first step in this process will be the collection of all subcomponent materials data sheets, acceptance testing, inventory & shipping records and other pertinent information necessary to create a track record from raw stockpiles, supplier packaging & storage and shipment/acceptance/inventory at MAF or other spray facilities. Independent chemical sampling and evaluation will baseline a chemical profile for all supplier materials through the use of High Performance Liquid Chromatography (HPLC), Fourier Transform Infrared Spectroscopy (FTIR), Fourier Transform ¹³C Nuclear Magnetic Resonance (FT-NMR) and other appropriate techniques to fully quantify raw materials constituent make-up including identification of contaminants. The raw materials are received as part "A" and "B" components. Part A is a mixture of isocyanates with predominantly diphenylmethane-diisocyanate (MDI) and Part B is the polyol component primarily of polyols, catalysts (amines & tin based), fire retardants (Fyrol, Dow & others), blowing agents (freons, CFC's & HCFC's) and various other unidentified elements. Analysis of these components in the past has produced a wide variance of proportional contribution to the delivered material.^{2, 10} The physical properties of the final foam material are directly related to the exact chemical proportion of the raw materials, process and environment as emphasized in all research to date. Quality control sampling must be event driven and/or sufficient bonded storage/handling controls in place.

Secondly, cured foam must be analyzed in an equally comprehensive manner to assure that not just through thickness chemical constituents meet functional requirements (e.g., FTIR), but density, thermogravimetric analysis (TGA), differential thermogravimetric analysis (dTGA), flame retardancy tests, combined environmental tests, mechanical tests, cryoflex testing, average cell wall thicknesses and possibly cell wall shape uniformity measurements. Witness samples, photographic surveillance, UV monitoring and other verification techniques need to be assessed against the baseline. These steps when combined with a thorough statistical process control philosophy will establish the baseline from which improvements are obtained.

Foam improvement methodologies will be immediately recognized through the strict process controls previously described and currently being implemented by the ET Project Office. A careful design of experiments approach including all variables in the current process, raw materials proportioning, mix ratios, substrate preparation and environment with specific attention to the respective change matrix sensitivities to strength, thermal,

heat recession and other physical properties will result in a range of improvement solutions. These improvements can be immediately introduced on the flight vehicle in locations without strict debris requirements for flight validation.

New Foam System Formulations – In previous foam formulation efforts conducted by NASA, researchers were successful in identifying industry available foam formulations meeting Shuttle requirements with some physical attributes exceeding existing foam performance.² For instance, a BASF Pluracol 975 & Mondur MR w/catalyst formulation showed only 3.30% weight loss by TGA at 300°C versus the NCFI-22-65 (precursor foam to NCFI 24-57 currently used on ET aft dome) weight loss of 13.85%. At 600°C, a Stepan Chemical Stepanol PS 3152 & Mondur MR formulation showed 62.95% versus the NCFI product's 95.50% weight loss by TGA.² There may very well exist current "off-the-shelf" foam systems that can be qualified for ET that outperform the existing foam systems as was the case in this specific instance in the late 1980's. However, a comprehensive industry wide search and screening must take place to identify viable candidates. Attention to research methods previously deployed and documented can drastically shorten the cycle for such screenings. Also, the author has suggested to the MSFC Shuttle Program Office that a contest or BAA be announced to spray foam manufacturers soliciting new foam formulations with a greater performance attribute.

Other long term solutions are necessary to begin in parallel to serve as "off ramps" or risk reduction activities should the performance of improvements and new foam formulations not provide the requisite debris reduction results in flight. These include coatings for surface stabilization, fiber reinforcements and combination systems.

Coatings – Paint, membranes and other high heat resistant barriers that can maintain the aerodynamic surface during the first few minutes of flight. These coatings must necessarily be highly compatible with the isocyanurate/polyurethane foams. A paint membrane was flown on the first ET on STS-1, but subsequently eliminated. Recent advances in polymer science may facilitate a "conversion" type top layer of foam of a higher density and, subsequently, higher modulus than the parent material. These tenacious type coatings with high heat resistance and high strength will necessarily require a full verification process under combined environmental loadings.

Fiber Reinforcements – This will include building on the current body of knowledge on polyurethane foams to optimize a formulation with high heat resistance and higher strength. Fiber reinforced foams offer a very high promise of being able to increase strength and further research/development is necessary.⁴ Some embryonic unfunded initiatives have begun to address this issue through an agreement with DuPont to exploit Kevlar® as a reinforcing fiber. The team has successfully integrated these fibers into a hand-spray version of Part B polyol (Arco Chemical Co., Thanol R-350X) and produced foam samples. Additional funding might help add the strict controls surrounding raw materials handling, fiber mixing, sample preparation, mix ratios and environmental constraints so important to quantifying this fiber integration. Future work should necessarily include strict process controls and data recording, sensitivity studies on fiber content and rise rates, volume fraction and chemical make-up. Also, alternate polyols

with lower viscosity values may improve the fiber mixing process eliminating the need to add volatile solubles. These fiber reinforcement solutions build on the foam improvements and new formulations offered in parallel and are more readily flight qualified by similarity.

Combination Systems – Each of the new fiber reinforcement foam formulations and coatings need not only be examined separately in meeting requirements, but in combination with one another. Such combination systems can leverage the entire materials improvement initiatives to realize true zero debris generation.

VI. Summary

We cannot afford to be defeated by the challenge placed before NASA. The development of more superior spray-on foam insulation is not a Shuttle specific issue. This materials development challenge can provide the environment to deliver technologies needed throughout the current NASA exploration mission such as insulation systems needed on the Crew Launch Vehicle (CLV), Crew Exploration Vehicle (CEV), lunar building blocks, inflatable structures and upper stages. Additionally, it may prove invaluable in an unexpected extension of Shuttle utilization should NASA not deliver on its latest architecture in a timely fashion. Compare any of the currently NASA funded technologies against this critical materials improvement initiative and one finds these initiatives rank much higher in priority across the full spectrum of NASA enterprises. Our leadership must and will rise up to do the heavy lifting of engineering excellence.

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